Energy Conservation and Indoor Air Quality:

Benefits of Achieving Both in Homes

As with commercial, education and healthcare buildings, the trend towards building green (sustainable) homes has taken hold. According to a survey conducted by the National Home Builders Association (NAHB) and McGraw-Hill Construction, the US residential green building market is expected to be 6 percent to 10 percent of all new residential construction by value (approximately $12 billion to $20 billion) by the end of 2008. It is expected to double to 12 percent to 20 percent ($40 billion to $70 billion) of market share by 2012 (McGraw-Hill Construction 2008a).

The survey results also showed that improving the quality of construction and the quality of life have emerged as the most important reasons for building green. Seventy (70) percent of homebuyers were more apt to buy green in today's economic conditions, and 87 percent were at least moderately knowledgeable about green home building. Homeowners cited lower operating costs (energy savings) (91%), having a healthier place to live (84%) and environmental concerns (80%) as the top three most important reasons for buying green homes. In 2008, builders ranked doing the right thing as their primary motivation for building green, but said that by 2013, quality will become their most important motivator (McGraw-Hill Construction 2008a, 2008b).

These results demonstrate that the message is finally beginning to resonate that homeowners' desire for healthy indoor environments ranks right up there with energy and environmental conservation. Yet, builders tend to focus more on energy and environmental conservation in their selection of green building features, such as tight construction, insulation, Energy Star products and water-efficient plumbing (McGraw-Hill 2008b). While these features are excellent choices for lowering energy costs and conserving water, they may inadvertently contribute to poor IAQ. As with commercial buildings, super tight, insulated homes with minimal ventilation and low air change rates can result in indoor mold growth and/or indoor air pollutants building up to sufficiently high levels as to threaten occupant health. Interestingly, commercial builders do a better job of balancing IAQ and energy conservation in commercial buildings. Some of the green products most often specified have an IAQ focus, including thermal and moisture protection (64 percent), finishes (62 percent), wood and plastics (57 percent), and furnishings (39 percent) (McGraw-Hill 2008a).

Poor IAQ also is a function of homeowners' lack of understanding about how to minimize indoor air pollution in their homes, such as controlling sources of indoor air pollutants and providing adequate ventilation and filtration. Conversely, to pursue good IAQ and quality construction without considering the efficient use of energy may unnecessarily increase construction and energy costs, financial hardships for families, and emissions of greenhouse gases, thereby contributing to outdoor air pollution and possibly even global warming. All those involved in building and renovating homes must strive towards adopting one defining common set of green principles that give equal emphasis on energy efficiency and protecting occupant health (good IAQ). The two must go together.

This white paper completes a three-part series on energy and indoor air quality, and looks specifically at energy and IAQ in homes, including a review of who is most at risk from indoor air pollution, common indoor air contaminants found in homes, their sources, health impacts and what steps can be taken to achieve the efficient use of energy and good IAQ. The other two white papers in this series, Energy Conservation and Indoor Air Quality: Partnering to Protect Human Health, and Energy Conservation and Indoor Air Quality: Lessons From the Past Have Relevance for the Future, are recommended reading for gaining a valuable perspective on the interdependence between IAQ and energy and the benefits of considering them as primary and complimentary goals for healthy indoor environments. They are available free of charge from the Aerias-AQS Indoor Air Quality Resource Center at www.aerias.org, Premium Content tab / White Papers.

Energy and IAQ: A Delicate Balancing Act

While it is very good news that green building has become a viable alternative to traditional building design and construction and is well positioned going forward into the 21st century, it has only been in the past 10 years or so that this approach has been applied to new home construction and it only the past couple of years that it has really gained traction. This is significant because 92 percent of the current US housing stock was built before 2000 (US DOE 2005). Almost three-quarters of homes are single-family residents (65 percent, single-family detached and 7 percent, single-family attached). Most homes are located in urban areas: cities (43 percent) and suburbs (20 percent) (American Fact Finder 2006, US DOE 2005). See Table 1 on page 3 for an overview of the current US housing stock.

What this means is most homes may not have good IAQ measures in place. Manufactured homes, which have become the primary housing choice among low-income people in rural areas and are used as temporary housing by the Federal Emergency Management Agency (FEMA), also have IAQ challenges that other types of residences, including green homes, do not (see the discussion below on Formaldehyde and Manufactured Homes for more information). Another concern is green building protocols often place less emphasis on IAQ than on energy and water conservation, recycling and protecting the outdoor environment, yet poor IAQ places nearly 40 percent of the US population at risk for serious health problems, including respiratory disease, cancer and developmental problems (based on data compiled by Lu et al).

To understand how energy affects indoor air quality in homes and how to use energy effectively and efficiently to achieve good IAQ requires an understanding of the primary sources of indoor air contaminants, who is most at risk and how best to minimize exposure to these contaminants. It also requires an understanding of energy's role in successfully applying the three primary strategies for good IAQ: source control, ventilation and air cleaning (filtration).

Indoor Air: An Intriguing, Complex Environment

All indoor air environments contain a myriad of visible and invisible contaminants. Airborne pollutants, including potential carcinogens, reproductive toxins and human irritants, are 2 to 10 times higher indoors when compared with outdoor levels and can be as much as 1,000 times higher in newly constructed and renovated indoor spaces. These visible and invisible contaminants generally fall in one of two categories: (1) particulates or (2) gases, vapors and odors. The following provides a very brief description of each category, and the health problems associated with them. For more detailed information about indoor air contaminants and who is at most risk from exposure, see the following white papers, which are available at no cost from Aerias (www.aerias.org) – Premium Content tab / White Papers:

- Clearing the Air on Indoor Air Cleaners / Purifiers
- IAQ and Sensitive Populations Groups
- Asthma and Damp Buildings: Making the Connection
- IAQ and Children's Health
- PBDE Flame Retardants and Indoor Environments: Where There's Smoke, There's Fire?
- Cleaning Chemicals and Their Impact on Indoor Environments and Health

Particulates: Size is Everything

Particulates are particles that are small enough to suspend in the air. Suspended inorganic particles, such as metals (lead, mercury); dust; pollen; asbestos and other fibers; car, bus and truck exhaust; or environmental tobacco smoke (ETS) and other types of smoke such as from fire places and cooking, are often referred to as aerosols. Suspended organic compounds and small living organisms, such as bacteria and viruses; mold spores and pieces of mold colonies; dust mite feces and body fragments; cockroach body parts; and dander from cats, dogs and other mammals, are called bioaerosols (McDonald and Ouyang 2000). Allergens, associated with grasses, pollen, dogs, cats, dust mites, cockroaches and mice to name a few common examples, also fall into this category. Particles can range in size from very small (0.001 µm to 10 µm), which can remain in the air for a long time, up to relatively large (100 µm), which quickly settle out of calm air (ALA Special Report on Air Cleaners).

Inhaling particulates can cause eye, nose and throat irritation and increase the risk for respiratory infections. Health care professionals are especially concerned about the long-term effects of inhaling fine particles (less than 2.5 µm – also referred to as $PM_{2.5}$ or fine PM), because they can travel deep into the lungs where they can remain embedded for years or be absorbed into the bloodstream. Inhalation of fine PM have been linked to increases in respiratory health problems such as asthma, bronchitis, pneumonia and emphysema; hospitalization for heart or lung disease; and even premature death.

Table 1. US Housing Characteristics (US DOE 2005, American Fact Finder 2006)

History of Housing Units Built		Types of US Housing	
Year / Location	Number Built (millions) / Percent	Type / Location	Number Built (millions) / Percent
Before 1940	14.7 (13%)	Single Detached	72.1 (65%)
1940 – 1969	32.4 (29%)	Single Attached	7.6 (7%)
1970 – 1979	18.9 (17%)	Apartments 2 to 4 units	7.8 (7%)
1980 – 1989	18.6 (17%)	Apartments 5 or more units	16.7 (15%)
1990 – 1999	17.3 (16%)	Mobile Homes	6.9 (6%)
2000 – 2005	9.2 (8%)		

Total	111.1 (100%)		111.1 (100%)
US Housing: Geographic Distribution		US Housing: Urban / Rural Locations	
Northeast	20.6 (19%)	Cities	47.1 (43%)
Midwest	25.6 (23%)	Towns	19.0 (17%)
Southeast	40.7 (36%)	Suburbs	22.7 (20%)
West	24.2 (22%)	Rural	22.3 (20%)
Total	111.1 (100%)		111.1 (100%)

The results of numerous studies have demonstrated a correlation between adverse health effects and the level of fine PM. In response, the US Environmental Protection Agency (US EPA) has established an aggressive program and standards to reduce fine PM levels in outdoor air. These same concerns also apply to indoor air in homes. See the discussion below on filtration for how to reduce the level of fine PM in residences. For more information and a comprehensive review of these studies, see Dockery et al 1993; Moolgavkar, Dockery and Pope 1994; Godleski et al 2000; US EPA Provisional Assessment of Recent Studies on Health Effects of Particulate Matter 2006; and the US EPA website on particulate matter, www.epa.gov/oar/particlepollution.

Larger particles (greater than 10 μm) do not cause as much concern, because they get caught in the nose and throat and are cleared from the respiratory tract by coughing or swallowing (ALA Special Report on Air Cleaners).

Gases, Vapors and Odors: What You Can't See Can Hurt You

The types of gases or vapors most often found in homes include combustion byproducts; pet, human and cooking odors; volatile organic compounds (VOCs); ETS; flame retardants; formaldehyde; and microbial VOCs and mycotoxins. Many of these substances also produce odors, some of which are pleasant while others can be distracting and irritating.

Combustion Byproducts. Combustion pollutants come from appliances that burn carbon-based fuels such as gasoline, natural gas, liquefied petroleum, kerosene, oil; coal, charcoal and wood. Examples of appliances that burn these fuels include space heaters, boilers, stoves (wood and gas), ovens, furnaces, fireplaces, grills, water heaters and clothes dryers. Carbon monoxide is a colorless, odorless gas produced by incomplete combustion of fuels. Nitrogen oxide, nitrogen dioxide, and sulfur dioxide are also gases formed during combustion, and unvented kerosene heaters may generate acid aerosols. Polycyclic aromatic hydrocarbons (PAHs) have been found stuck to tiny soot particles in car exhaust, which can find their way into the indoor environment.

In most US homes, combustion byproducts do not pose a significant threat to health, as most appliances that burn fuels are usually safe. Exposure to these pollutants at high enough levels, especially carbon monoxide, can produce serious illness and even death, however. As noted above, fine PM is not only an irritant but also can cause respiratory illnesses. Homeowners should make sure appliances are working properly and used only in well-ventilated rooms. Outdoor cooking grills should never be used indoors or on balconies, as they are not only a fire hazard, but using them in close proximity to windows, doors or outdoor air intakes allows the smoke to easily get inside homes.

Volatile Organic Compounds. Among the most prevalent of all indoor air constituents are volatile organic compounds (VOCs), with as many as 100 to 1,000 different VOCs in the air where children can easily inhale them. Volatile organic compounds are emitted from a wide variety of sources, including building materials, home furnishings, paint, carpets, air fresheners, and personal care, and cleaning products and processes. Air Quality Sciences, Inc. has measured VOC levels in hundreds of homes, schools and offices. Table 2 lists the 14 most commonly found VOCs in homes and their sources.

Table 2. Common VOCs found in homes

VOC	Source(s)	VOC	Source(s)
Toluene	Cleaners, construction materials	Hexanal	Cleaners, Woods, deodorizers
Styrene	Plastics, flooring	2-Butoxyethanol	Wood finishes, cleaners, paints
Siloxanes	Waxes, polishes, deodorants	Ethanol/Isopropanol	Cleaners, disinfectants
Formaldehyde	Furniture, shelving, cabinetry	TXIB	Paints, Plastics
Hexane	Cleaners, polishes	Acetaldehyde	Plastics, wood finishes, insulation
Limonene	Fragrances, cleaners	Longifolene	Cleaners, wood products, adhesives
Pinene	Woods, cleaners	4 Phenylcyclohexene	Carpet, papers

Test results also showed that the average total VOC (TVOC) level was 650 µg/m^3, with a minimum of 120 µg/m^3 and a maximum of 26,000 µg/m^3. Most standards and guidelines consider 200 µg/m^3 to 500 µg/m^3 TVOC as acceptable. Levels higher than this may result in irritation to some people. While TVOC is a good indicator of elevated VOCs and complicated VOC mixtures that may lead to irritation, minimizing the presence of specific chemicals with known health hazards is required to lower TVOC levels.

A new study compared human exposure to VOCs in homes, offices and outdoors and found that the largest contribution of VOCs to the personal exposure is from homes in the range of 42 percent to 73 percent, followed by outdoors, 18 percent to 34 percent, and offices, 2 percent to 38 percent. Benzene, dodecane, decane, methyl-cyclopentane, and trichloroethylene dominated outdoor VOC levels; methyl-cyclohexane, nonane, octane, tetraethyltoluene, undecane were highest in the offices; and 3-carane, limonene, a-pinene, b-pinene and the aromatics toluene and styrene were the most commonly found in the homes studied (Gokhale et al 2008).

Some VOCs can cause eye, nose and throat irritation; cough; headache; general flu-like illnesses; skin irritation; and some can cause cancer. Others produce odors that may be objectionable. A recent study also has found that children exposed to high levels of VOCs were four times more likely to develop asthma than adults (Rumchev et al 2004). Other studies also have found an association between VOCs and asthma in children (CARB 2005).

Complicating matters is the potential for interactions of VOCs with other chemical compounds to form a third compound that also may be a threat. As a result, even though the concentrations of individual VOCs may be well below odor thresholds or known toxic levels, their occurrence in complex mixtures may lead to perceived poor IAQ or irritation among those exposed. Various studies, for example, have shown that certain VOCs may react with ozone to produce a number of toxic compounds; such as, d-limonene and other terpene compounds, which are used in polishes, scented deodorizers, cigarettes, fabrics and fabric softeners, and can readily react with low concentrations of ozone, brought in from the outdoors or produced by ionizing air cleaners. This reaction creates aldehydes and ultrafine particles (Sarwar et al 2002; Weschler and Shields 1999; Wolkoff et al 2000, Apte and Erdmann 2002). The results from another study demonstrated that a mopping agent containing terpene generated vast numbers of ultrafine particles in a reaction with ozone. The results also showed that 10 minutes of mopping with this agent influenced indoor particle concentration for more than 8 hours (Long et al 2000).

Within two hours of certain cleaning processes, the TVOC levels can increase significantly, ranging from 40 µg/m^3 to 25,000 µg/m^3 (micrograms per cubic meter), and reach levels higher than the acceptable value (500 µg/m^3 or 0.5 mg/m^3) for VOC emissions from cleaning products, established by the GREENGUARD Environmental Institute, an independent third party certification program for low-emitting products used in indoor environments. This is important, because nearly all adults do some cleaning each day – an average of 20 to 30 minutes (Wiley et al 1991). Results of activity pattern surveys of California adults found that 26 percent were near or used cleaning agents on the day on which they were surveyed and 31 percent reported that they were near or used scented air fresheners (Jenkins et al 1991). For a more detailed discussion of health risks associated with cleaning products and processes, please see the white paper, Cleaning Chemicals and Their Impact on Indoor Environments and Health.

In addition, a growing number of scientists are concerned that exposure to very small traces of VOCs and some industrial chemicals in homes and schools may have profound impacts on fetuses, newborns and children, including disruptions to the endocrine system (hormones), gene activation and brain development. Along those same lines, there is concern about an apparent increase in the number of children diagnosed with autism spectrum disorders (ASD), and as with asthma they wonder if there is a connection with exposure to indoor air contaminants. Estimates suggest that around 6 in 1,000 people in the world suffer from ASD, with more boys affected than girls. The increase in prevalence of ASD is partially due to changes in diagnostic criteria, terminology and increased reporting. Although there are as yet no conclusive links between autism and chemical exposure, a recent review of scientific literature on the causes of neurodevelopmental disorders implicated a number of industrial chemicals including lead, methylmercury, polychlorinated biphenyls, arsenic and toluene (Grandjean and Landrigan 2006).

At this time, research in this area is still new, and as yet results do not present a clear picture. One study of particular note, the National Children's Study, sponsored by the US EPA and the Centers for Disease Control and Prevention (CDC), is in progress with results expected in 2010. By the time the study is completed, about 100,000 children at various ages from birth to puberty will have participated. Among the primary goals is to investigate the associations between exposures to environmental pollutants, such as VOCs among others, and health problems, especially asthma, autism, attention deficit disorder and alterations at puberty caused by hormonal disruptions and other neurobehavioral and neurocognitive disorders (Özkaynak et al 2005). Please see the white paper on IAQ and Children's Health for a more detailed discussion.

Environmental Tobacco Smoke. Although becoming a lesser issue in public buildings, exposure to environmental tobacco smoke (ETS – also called passive smoke or secondhand smoke) is still found in many homes, which is particularly dangerous for children. According to the CDC, nearly 60 percent (22 million) of children ages 3 to11 years are exposed to secondhand smoke and about 25 percent of those children live with at least one smoker (CDC 2006). Younger boys (ages 0 to 2 years) spend more time around ETS than older boys, and more girls spend more time around ETS than boys, all which are indicative of children's typical activity patterns. Girls and younger children spend more time indoors than boys and older children (Wiley et al 1994).

Children, who are exposed to ETS, are more likely to develop lower respiratory tract infections, bronchitis, pneumonia, middle ear disease, sudden infant death syndrome (SIDS) and respiratory symptoms than children who are not exposed (CDC 2006). Environmental tobacco smoke also can play a role in the development and exacerbation of asthma. Exposure to ETS is well documented as a major risk factor for respiratory problems and cancer for people of all ages. The US Surgeon General has determined that there is no risk-free level of exposure (CDC 2006). Environmental tobacco smoke alone contains more than 4,700 airborne substances, including gases and particles from incompletely burned tobacco, of which 243 are known carcinogens.

Flame Retardants. Polybrominated diphenyl ethers (PBDEs) are common flame retardants, which are used in a wide variety of materials, products and applications. Even though PBDE flame retardants have saved numerous lives, manufacturers of products containing them are under increasing pressure to phase out these chemical compounds in favor of other flame retardants considered less toxic. At issue is whether the benefits of PBDEs outweigh increasing evidence that these chemicals rapidly accumulate in the environment and in human blood and body fat, and because of their structural similarity to polychlorinated biphenyls (PCBs) may have the potential to cause serious heath problems, including cancer, disruptions to the human endocrine (hormone) system and neurologic damage. In addition to food and human breast milk, results of recent studies have demonstrated that indoor environments may be a significant source of PBDEs as they have been found in house dust and on the greasy film found on windows (Rudel 2003, Butt et al 2003).

Results of a recent study seem to bear this out. Specifically, chemical ingredients of penta-BDE were found in the dust of California homes at 4 to 10 times the levels found elsewhere in the US and 200 times higher than in Europe. Some of the California homes studied had levels higher than have ever been previously detected in household dust. The researchers also found double the amount of penta-BDEs in the blood of California residents compared with the nationwide average. The researchers concluded that the results of this study demonstrate that California's unique furniture flammability standard, requiring furniture to be fire resistant to an open flame for 12 seconds, has led to increased exposure to penta-BDE, a commercial flame retardant mixture added to polyurethane furniture foam to meet the standard. Although penta-BDE production in the US ended in 2004 following bans in several states, including California, furniture treated with the chemical may be present in many homes. In addition, most states have not banned the use of penta-BDE in imported furniture (Zota et al 2008). For a more detailed discussion of flame retardants containing PBDEs and IAQ, see the white paper, PBDE Flame Retardants and Indoor Environments: Where There's Smoke, There's Fire?

Formaldehyde in Manufactured Homes. Formaldehyde is used widely by industry to manufacture building materials and numerous household products, and also is a by-product of combustion and certain other natural processes. Primary sources include pressed wood products such as particleboard (PB), hardwood plywood (HWPW), hardboard (HB) and medium density fiberboard (MDF); finished furniture, shelving, and cabinetry made with composite boards and certain coatings; counter tops, decorative fabrics and textiles; and paper products. It also may be used as a biocide in certain paints and coatings, adhesives, and personal care items. Medium density fiberboard contains a higher resin-to-wood ratio than other urea-formaldehyde pressed wood products and is generally recognized as being the highest formaldehyde-emitting pressed wood product.

Formaldehyde is a colorless, pungent smelling gas that primarily results in irritation to the eyes, nose, throat and skin. According to the CDC, acute and chronic health effects from exposure to formaldehyde vary depending on individual sensitivity, with sensitive individuals reporting symptoms at 100 ppb (0.1 ppm) or less. This upper respiratory tract irritation can potentially exacerbate asthma symptoms and other respiratory illnesses, but there is no evidence that exposure to formaldehyde causes asthma, nor is it considered to have reproductive or developmental effects on humans. Whether or not formaldehyde causes cancer has been extensively studied and debated over the past 30 years and remains controversial.

The US Environmental Protection Agency, for example, has classified formaldehyde as a probable human carcinogen under conditions of unusually high or prolonged exposure. The International Agency for Research on Cancer (IARC), however, upgraded its initial classification of formaldehyde as a probable human carcinogen to a known human carcinogen in 2004. The California Air Resources Board supported the IARC findings by classifying formaldehyde as a "toxic air contaminant" after state experts concluded that based on current research, there is "no safe exposure threshold [for formaldehyde] … to preclude cancer."

In response to health concerns with formaldehyde, CARB, in April 2007, voted unanimously to pass the toughest, most comprehensive production standard in the world for formaldehyde emissions from composite wood panels. The state of California determined that inhalation of formaldehyde from composite wood products containing urea formaldehyde resins is one the primary sources for human exposure. According to the California regulation, all HWPW, PB and MDF panels will be required to meet certain product emission standards with full implementation by the year 2012. Allowable emission levels are significantly lower than the 1985 HUD standard levels and include: 130 ppb (0.13 ppm) for thin MDF, 110 ppb for MDF (0.11 ppm), 90 ppb (0.09 ppm) for PB and 50 ppb (0.05 ppm) for HWPW with a composite core or veneer core. All products must be third party certified for verification of emissions and a strict chain of custody will apply. A number of other states are considering adopting similar emission standards. The California Air Resources Board is implementing its new limits in two phases starting January 2009, with the final limits in place by 2012.

Based on more than 300 measurements collected in residences, office buildings and schools, AQS studies have found typical concentrations range from 0.01 ppm to 0.03 ppm in office buildings and 0.05 ppm to 0.08 ppm in homes. An average level of 0.04 ppm has been found in schools, with new or recently renovated or refurbished school environments reaching 0.14 ppm.

Recent CDC studies of manufactured homes used by FEMA for temporary housing provide strong evidence for continued concern about the use of formaldehyde-containing products in these homes. Between December 21, 2007 and January 23, 2008, CDC investigators tested a random sample of 519 FEMA-purchased manufactured homes and found average formaldehyde levels of about 77 ppb (0.077 ppm) – more than twice the level that the CDC says is usually found in residential indoor environments (10 ppb to 30 ppb or 0.01 ppm to 0.03 ppm) (CDC 2008).

These findings are significant not only for those living in FEMA housing, but also for low-income Americans for whom manufactured homes have become the primary housing of choice, especially in rural areas. Between 1990 and 2000, the number of manufactured homes grew by 25 percent to represent 16 percent of all owner-occupied rural housing stock (MacTavish, Eley and Salamon 2006).

Manufactured homes are somewhat unique when compared with conventional homes in that there are primarily constructed using pressed-wood products. They also have less efficient HVAC systems than conventional homes, as demonstrated by researchers at the National Institute of Standards and Technology (NIST), who installed a new, doublewide manufactured home the NIST campus in Gaithersburg, Maryland for ventilation, energy and indoor air quality studies. They found that the building envelope and air distribution ductwork were fairly leaky, but not unusually high for typical US manufactured homes. In addition, results indicated that the airflow rates of the local exhaust fans (bath and kitchen) are significantly below the US Housing and Urban Development (HUD) requirements (Persily et al 2003).

Microbial VOCs and Mycotoxins. Moisture also is a vapor that must be monitored as too much moisture can support indoor mold growth. In homes, sources of moisture include plumbing leaks, poorly ventilated kitchens and bathrooms, building envelope and window leaks, and poorly balanced and maintained HVAC systems. See the discussion below on Contributions of Energy to Indoor Air Quality, Building Envelope. Some types of mold also emit VOCs, known as microbial VOCs or MVOCs, which are responsible for the characteristic musty, earthy odors associated with mold. Children who are sensitive to MVOCs may experience eye, nose and throat irritation. A wide variety of molds also can produce mycotoxins at various times during their lifecycles. Children can experience potentially serious health problems if they are exposed to high levels of these compounds, but this is rare in most indoor environments.

Asthma and Indoor Air in Homes

In recent years, educators, parents, physicians and pubic health officials have been very concerned about the dramatic increase in the number of children who have developed asthma and possible connections to indoor air pollution. From 1980 to 1994, for example, the proportion of Americans with asthma increased by 75 percent. In children under the age of five, the proportion grew by 160 percent (AAAAI 2005).

Analysis of data from a national sample of 17,110 children ages zero to 17 years indicate that all children living in urban settings are at increased risk for asthma (Aligne et al 2000). Public housing, especially apartment homes in urban settings, is more likely to have cockroach, rodent and mold infestations. Allergens from cockroaches, rodents and mold are known allergy and asthma triggers. Public health departments of Seattle and Kings County, Washington analyzed trends in local hospitalizations for children with asthma from 1987 to 1998. The results showed that the youngest children in the poorest urban communities have the highest rates on asthma hospitalizations (Solet et al 2000).

In addition, results of two landmark studies provide the first solid evidence that damp buildings and exposure to mold bioaerosols is a risk factor for developing asthma and not just in making asthma symptoms worse. They also found that the risk for developing asthma appears higher for, but is not limited to, children who are sensitive to mold allergens or who have parents with asthma (Jaakkola et al 2005, Cox-Ganser et al 2005). For more information, see the white papers Asthma and Damp Buildings: Making the Connection and IAQ and Children's Health.

Poor IAQ in Homes Not Just A Risk Factor for Children

At the other end of the age spectrum, older people also are at a greater risk for adverse health effects from exposure to indoor air pollutants. One factor is as people age their immune systems become less effective. As a result, autoimmune disorders and cancer become more common. In addition to autoimmune diseases, older people have a greater risk for developing cardiovascular and respiratory diseases. Epidemiological studies conducted worldwide have shown a consistent, increased risk for cardiovascular events, including heart and stroke deaths, in relation to short- and long-term exposure to concentrations of pollution, especially fine PM (Brook et al 2004). Results from other studies have demonstrated that exposure to indoor air pollutants, such as VOCs from household products, may not only increase the risk in older people of developing asthma and chronic obstructive pulmonary disease (COPD), which includes chronic bronchitis and emphysema, but also neurologic and cognitive effects, motor dysfunction and loss of visual acuity (Farrow et al).

People with chronic illnesses also are at increased risk for adverse health effects from indoor air pollution. In 2005, 133 million people, almost one-half of all Americans lived with at least one chronic condition, the most prevalent of which are allergies, asthma, cardiovascular disease (primarily heart disease and stroke), cancer and diabetes. Chronic, disabling conditions also cause major limitations in activity for more than one (1) of every 10 Americans, or 25 million people, which means it is likely these people spend nearly all of their time at home. Chronic diseases also account for 70 percent of all deaths in the US (CDC 2008).

People who are waiting or have recently had organ transplants are another high risk group, as again, their immune systems may be impaired, which severely limits their ability to fight off infections and disease, and in general may make them more sensitive to irritants. For a more detailed discussion of people at high risk from poor IAQ, please see the white paper IAQ and Sensitive Populations Groups.

Contribution of Energy to Indoor Air Quality

So what does this have to do with energy use in homes? It is well documented that the energy conservation strategies since the 1970s and continuing today have an unintended effect on the health of building occupants and eventually spawned an epidemic of indoor mold growth, which peaked just after the turn of the millennium. What is not so well known is that confounding these problems was a shift from natural to synthetic materials used to construct, finish and furnish building and home interiors, leading to significant off gassing of VOCs, including formaldehyde, which became a major problem for all buildings with mechanical ventilation, including homes. In addition, electronic office equipment has become a mainstay. Copiers, computers, and printers may generate ozone, particles, and VOCs. That's the bad news; the good news is energy is also the primary driver behind two of the three strategies for good IAQ. No matter the type or size or type of the home – single family home (detached or attached), apartment (low-rise or high-rise) or manufactured home – creating and maintaining good indoor air quality requires three key strategies: source control, ventilation and air cleaning, which starts during the design and construction phases and continues throughout a building's life. It is never too late to start managing IAQ in older homes. Indoor environmental experts recommend these three primary strategies, especially when integrated into a home's overall operation and maintenance. The following highlights each of these strategies.

Source Control – Indoor Air Contaminants. The US Environmental Protection Agency, the American Lung Association and other experts agree that source control is the only completely effective way to remove pollutants from indoor environments. They also agree that total eradication of indoor air contaminants often is not feasible or practical, especially in homes. A more realistic goal is to use building materials, furnishings, finishes, office equipment, and cleaning products and processes that emit low levels of non-toxic VOCs. Surface cleaning also removes larger particles and kills bacteria and viruses on floors, furniture, walls, doorknobs, bedding and linens, and bathroom fixtures. In addition, keeping the heating, ventilating and air-conditioning (HVAC) system in good working order and air ducts and drip pans clean is important for minimizing dust and particle accumulation and indoor mold growth within the system.

The GREENGUARD Environmental Institute (GEI) has a standard and product certification for low-emitting products and materials for use in daycare and school facilities, which is also applicable to homes. The tough GREENGUARD Certification for Children & Schools is an extension of the established

GREENGUARD Indoor Air Quality Certification Program. This standard presents the most rigorous product emissions criteria to date. The following summarizes key provisions in the standard, requiring that all construction and furnishing products meet these emission levels within seven days of installation. This standard limits acute (irritation and odor) and long-term chronic exposure effects (Table 3).

Table 3. GREENGUARD Emission Standard for Educational Environments (see bullets following the table for important notes)

Chemical	Allowed Emission Contributions
TVOC	≤ 215 µg/m³
Formaldehyde	≤ 0.0135 ppm
Total Aldehydes	≤ 0.043 ppm
Individual VOCs	≤ 1/100 TLV or ½ CA Chronic REL (whichever is less)
Total Phthalates	≤ 10 µg/m³
Total Particles (≤ 10µm)	≤ 22 µg/m³

Notes:

Total phthalates include dibutyl (DBP), diethylhexyl (DEHD), diethyl phthalate (DEP), dibenzyl phthalate, (DBzP), diisobutyl phthalate (DIBP), and diethyl (DEP), common material related phthalates.

Identified VOCs measured in mass spectrometric scan of C_6 - C_{16} hydrocarbon range, evaluated for presence on ACGIH/TLV list and CA CREL list. TVOC includes all measured VOCs in scan range calibrated to toluene.

Total aldehydes include 2-Butenal, Acetaldehyde, Benzaldehyde, Benzaldehyde 2,5-dimethyl, Benzaldehyde 2-methyl, Benzaldehyde 3- and/or 4-methyl, Butanal, Butanal 3-methyl, Formaldehyde, Hexanal, Pentanal, and Propanal.

Particles applicable to fibrous, particle-releasing products with exposed surface area or particle generating process

Research has demonstrated the value of source control as the primary IAQ strategy. A Korean study, for example, continuously monitored VOCs during three years in new and older homes. The VOC levels in the new homes decreased markedly after one year, and steady emissions of VOCs were obtained in the initial months. Formaldehyde and a-pinene related to pressed wood materials need a longer flushing period than the other VOCs in the new homes. The levels of VOCs in the older homes showed no significant fluctuation during the three-year period. The results indicated that decreases in VOCs levels in the new homes were influenced more by time (the older the home, the less VOC emissions) than by the HVAC systems (Park and Ikeda 2006).

An important note: When seeking to reduce VOC levels in indoor air, it is important to realize that many “low-VOC” products, even those certified as green or environmentally friendly, are rated by their VOC content not by their VOC emissions. Measuring VOCs by weight or content (usually measured as grams per liter minus water) does not give a clear picture of how much of a particular VOC or the total amount of all VOCs (TVOC) from a product may be getting into the air. Nor does it give an accurate picture of how VOC emissions from a product will affect the total VOCs in the area in which it is being used. The only way to be sure a product does not emit high levels of VOCs is to actually measure VOC emissions (usually measured as micrograms per square meter per hour) through emissions test methods like those used in the GREENGUARD Certification program. It is the VOC emissions that contribute to indoor air pollution; not VOC content.

Source Control – Water and Moisture. Source control also involves inspecting the home regularly inside and out for any signs of water damage, which is a good indicator that moisture levels are high enough to support indoor mold growth. If water damage or signs of mold are found, they should be remediated immediately. The best way to prevent indoor mold growth is to eliminate all sources of excess moisture, from leaks in the building envelope, improper building pressurization, an inefficient or malfunctioning HVAC system, and appliances to building occupant activities. A malfunctioning or poorly maintained HVAC system also uses more energy than a well-maintained system.

Ventilation. Ventilation and air cleaning are invaluable for picking up where controlling sources of indoor air pollutants leaves off. The two work hand-in-hand, as many types of air cleaners are an integral part of the HVAC system. A well-designed and properly operating HVAC system brings in and conditions outdoor air and circulates the air through the building. The primary benefit beyond warming, cooling and managing the humidity the air is to dilute indoor air pollutants to minimize their impact on the indoor environment and building occupants. The HVAC system also transports indoor air contaminants outside.

The best type of HVAC system depends the size of the home, whether it is detached, attached, multi-stories, or a low-rise or high-rise apartment building, along with a wide variety of other factors that are outside the scope of this paper. The key is to ensure that the system is properly designed for the space and properly balanced, operated and maintained. It also is vital that the HVAC system maintain appropriate building pressurization, which is critical for preventing moisture intrusion. The downside of HVAC systems is they may bring in outdoor air pollutants as well as pick up indoor pollutants, such as mold spores, allergens, dust and VOCs from one area of the home and transport them to another.

Air Cleaning / Filtration. Simply stated, with respect to air cleaning, also referred to as filtration, the goal is to remove indoor pollutants by trapping them inside a mechanical device. Effective air cleaning:

- Protects HVAC systems and components
- Protects furnishings and décor of occupied spaces
- Reduces housekeeping and building maintenance
- Reduces furnace and heating equipment fire hazards

- Protects building occupants (USEPA 2006, ALA Special Report on Air Cleaners)

Experts emphasize, however, that air-cleaning devices alone cannot ensure good IAQ, particularly where ventilation itself is inadequate (USEPA 2006). Air cleaners / purifiers employ various types of filtration technologies, which can be attached to HVAC systems or used in portable units that can be moved from room to room. The following is a brief description on the different types of filtration technologies. For a more detailed discussion, see the AQS white paper, Clearing the Air on Indoor Air Cleaners / Purifiers.

Mechanical filtration captures particles in a filter via physical mechanisms without electrostatic forces characterizes this air cleaning method. A common misperception is that fibrous filters (the most extensively used in mechanical filtration) work like a sieve, with particles becoming trapped within the spaces between the fibers. What actually occurs is that once the particles make contact with the fibers, they remain attached due to strong molecular forces between the particles and fibers. As a result, the particles become a part of the filter structure and contribute to a filter's efficiency by creating resistance of air flowing through the filter. Mechanical filtration works best at capturing large (greater than 0.5 µm) or very small particles (less than 0.2 µm). Because of the opposing trends in how large and very small particles behave in the air stream, mechanical filters are less efficient at capturing particles measuring between 0.1µm to 0.4 µm. (McDonald and Ouyang 2000).

The two filters often used in commercial and residential HVAC systems are pre-filters and high- efficiency particulate air (HEPA) filters. Some box or pleated type filters can be as thin as 2 inches to 4 inches or as wide as 8 inches to 12 inches. A bag type HEPA filter can extend up to 24 inches. Bag type filters typically have a lower pressure drop than the pleated or box type HEPA filters. Pre-filters and HEPA filters, whether bag or box type, will filter particles as small as 1 µm or less, but with varying efficiencies. Different filters have different air pressure drop characteristics, which is a factor in energy and cost analysis (Penn State 2006).

High-efficiency particulate air filters are typically rated as 99.97 percent effective in removing dust and particulate matter above 0.3 µm, based on DOP (diocytl phthalate) testing. In theory, HEPA filters should be highly effective against bacteria and fairly effective against viruses, but real world installations do not always achieve performance as measured in laboratories. Pre-filters are typically 70 percent to 90 percent efficient. Ultra low penetration air (ULPA) filters are like an ultra-HEPA filter, which are designed to capture 99.999 percent of all airborne particles 0.3 µm or smaller (AHAM 2006).

Electronic filtration devices use electrostatic forces to trap particles. In commercial or industrial applications, these devices are referred to as charged media precipitators or electrostatic precipitators (ESPs). In residential applications, they are called electronic air cleaners, some of which are portable and can be moved from room to room. The simplest form of electronic air cleaner is the negative ion generator, which uses static charges to make the particles larger and thus they settle out of the air faster (Penn State 2006).

Small electrostatic precipitators designed for home or other non-industrial applications do not have rappers, so they must be taken apart and cleaned from time-to-time. Further, these devices are often inserted into airstreams without regard to air velocities, and as a result efficiencies can be much lower than those used in industrial applications. A well-designed electronic air cleaner for home or office building applications would not only be relatively large but also may have a high-energy demand (Penn State 2006).

Some air cleaners are designed to remove gases, vapors and odors as well as particulates. The removal process, called adsorption, is relatively simple in that air passes through an adsorption bed(s), which filters out the gases, vapors and odors. Adsorption beds are made up of sorbents. Solid sorbents, such as activated carbon, are especially useful for removing diesel fumes, hydrocarbons, ETS, body odor, cooking odors and some VOCs.

Ozone is a very reactive compound that is easily generated in hazardous concentrations by air passing through an electrostatic field. In air cleaning, ozone is used to remove odors from odor-causing VOCs while leaving a fresh, clean smell like after a thunderstorm. Some manufacturers, however, use ozone to remove odors from odor-causing volatile organic compounds (VOCs). They tout their products as superior, because they produce “activated oxygen,” “super oxygenated” or “energized oxygen,” and thus imply that ozone is a healthy kind of oxygen (CARB 2006). After all, ozone in outdoor air is what causes the fresh clean smell after a thunderstorm. Why not have those fresh, clean smells indoors?

What these manufacturers may not be telling consumers is that products that generate ozone for the purpose of air cleaning may be producing ozone at high enough levels as to put building occupants at significant risk for health problems. In fact, CARB recommends consumers not use these air cleaners. The CARB website (www.arb.ca.gov/research/indoor/o3g-list.htm) lists ozone generating air cleaners that the state of California recommends consumers avoid.

Research results have shown that ozone as an air cleaner or purifier is not particularly effective and as noted can be hazardous to health (Underhill 2000). The US Environmental Protection Agency website features summaries of other studies regarding the effectiveness of ozone generating air cleaners. The webpage titled Ozone Generators that are Sold as Air Cleaners may be accessed at www.epa.gov/iaq/pubs/ozonegen.html.

What has health professionals and regulators so concerned, besides attempts to take advantage of unsuspecting consumers, is ozone is a very strong lung irritant, which can exacerbate respiratory disease. It also can react with VOCs in indoor air to produce additional VOCs such as aldehydes, which have a more unpleasant odor, are far more irritating and more toxic than other VOCs (Boeniger 1995). Further, unreacted ozone at low concentrations around 120 ppb (0.12 ppm) can cause eye irritation, visual disturbances, headaches, dizziness, dry mouth and throat, chest tightness and coughing (Sittig 1991).

In September 2007, CARB approved a regulation to limit the concentration of ozone emissions from indoor air cleaning devices. This regulation went into effect in October 2008. It requires that manufacturers must have compliant products on the store shelves within two years of the regulation effective date or risk losing retail shelf space and perhaps face citations and fines for noncompliance.

Actually, manufacturers have two compliance dates to meet. First, as required by Section 94807, they must notify their distributors, retailers and sellers about the regulation and provide copies of the final regulation to them. They also must provide documentation to the CARB that this has been accomplished by October 18, 2009. Second, all air cleaner models marketed or sold in California must be tested, certified, and labeled as required by the regulation by October 18, 2010. Certification is achieved by having their products tested by a nationally recognized testing laboratory to the revised edition of UL 867, the Standard for Safety of Electrostatic Air Cleaners. Instructions for certification may be found at on the CARB website (www.arb.ca.gov/research/indoor/aircleaners/certification.htm).

Underwriters Laboratories (UL), a world leader of product safety testing and certification services and one of the two national testing laboratories selected by the state of California to provide this testing, is partnering with AQS to test and certify indoor air devices against an improved UL 867 ozone emission standard. The new CARB regulation is expected to impact approximately 60 to 80 consumer appliance manufacturers of indoor air products.

A Final Word

Energy conservation and IAQ are two sides of the same coin. If impacts on IAQ are not considered, energy conservation measures can cause significant health and comfort issues for families. On the other hand, if energy use is not considered when employing the three key IAQ strategies, source control, ventilation and air cleaning, energy costs may actually increase. As noted at the beginning of this report, to successfully manage IAQ and energy, both must have the same priority throughout the life of a home.

AQS stands ready to partner with homebuilders, designers, specifiers, and operation and maintenance personnel to create and maintain healthy indoor environments. AQS also standards ready to home air cleaner manufacturers with its state-of-the-art ozone test facility. United Laboratories and AQS will be monitoring other potential developments in order to meet anticipated demand driven by the CARB requirements. Visit us at www.aqs.com to learn more about how the AQS Production Evaluation Services can help you, or call us at (770) 933-0638. Also visit the AQS Aerias IAQ Resource Center to learn more about indoor air quality. Aerias may be accessed from the AQS website or at www.aerias.org. For a listing of products that are certified to emit low levels of VOCs, visit the GREENGUARD Environmental Institute at www.greenguard.org.

Citations

ALA Special Report on Air Cleaners: Types, Effectiveness and Health Impact. Available online at www.lungusa.org/site/pp.asp?c=dvLUK9O0E&b=39289. Accessed January 31, 2006.

Aligne, CA et al. Risk factors for pediatric asthma: Contributions of poverty, race and urban residence. Am J Respir Crit Care Med 2000; 162:873 – 877.

American Fact Finder. Housing: Physical Characteristics. 2006 American Community Survey. US Census Bureau. Washington, DC. Latest revision: September 2007. Accessed October 1, 2008. Available online at http://factfinder.census.gov.

Apte MG and Erdmann CA. Indoor carbon dioxide concentrations, VOCs, environmental sensitivity association with mucous membrane and lower respiratory sick building syndrome symptoms in the BASE study: Analysis of the 100 Building dataset. LBNL 51570. Lawrence Berkeley National Laboratory. Berkeley, CA. 2002. Available online at http://eetd.lbl.gov/ied/viaq/pubs/LBNL-51570.pdf.

Asthma Statistics, Media Resources: Media Kit, American Academy of Allergy, Asthma and Immunology. Milwaukee, WI. 2005. Accessed September 15, 2005. Available at http://www.aaaai.org/media/resources/media_kit/asthma.stm.

Association of Home Appliance Manufacturers (AHAM). About Air Cleaners. Washington, DC. 2006. Available online at www.cadr.org/consumer/air_cleaners.html. Accessed June 21, 2006.

Boeniger, MF. Use of ozone generating devices to improve indoor air quality. Am. Indust. Hyg. Assoc. J. 56:590 – 598. 1995. As reported in Underhill 2000.

Brook RD, Franklin B, Cascio W. Air pollution and cardiovascular disease: a statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. Circulation. 2004; 109:2655 – 2671. Available online at http://circ.ahajournals.org/cgi/content/full/109/21/2655.

Butt CM, Diamond ML, Truong J, et al. Spatial distribution of polybrominated diphenyl ethers in southern Ontario as measured in indoor and outdoor window organic films. Environ Sci Technol. 38(3): 724-731. 2004. Web release date December 17, 2003.

California Environmental Protection Agency Air Resources Board. Fact Sheet: Beware of ozone generating indoor "air purifiers." California Air Resources Board. Sacramento, California. March 2006.

CARB. Draft Report to the California Legislature: Indoor Air Pollution in California. California Air Resources Board. Sacramento, California. February 2005.

Centers for Disease Control and Prevention (CDC), Coordinating Center for Health Promotion, National Center for Chronic Disease Prevention and Health Promotion, Office on Smoking and Health. The health consequences of involuntary exposure to tobacco smoke: A report of the Surgeon General. Atlanta, Georgia. 2006. Available online at http://www.surgeongeneral.gov/library/secondhandsmoke/report/.

CDC Releases Results of Formaldehyde Level Tests. FEMA and CDC Joint Press Release, February 14, 2008. Available online at www.cdc.gov/od/oc/media/pressrel/2008/r080214b.htm.

Centers for Disease Control and Prevention. Chronic Disease Overview, Chronic Disease Prevention. Atlanta, Georgia. Latest update: March 2008. Available online at http://www.cdc.gov/nccdphp/overview.htm.

Cox-Ganser JM, White SK, Jones R, et al. Respiratory morbidity in office workers in a water-damaged building. Environ Health Perspect. 113(4): 485 – 490. April 2005.

EIFS Industry Members Association (EIMA). EIFS Performs: Excellent Choice in Mixed, Coastal, Hot, Humid Climate for Energy Efficiency, Temperature and Moisture Control. Executive Summary. Morrow, Georgia. 2008. Available online at www.eima.com.

Dockery DW, Pope CA, Xu X et al. An association between air pollution and mortality in six US cities. N Engl J Med 339 (24): 1753 – 1759. December 9, 1993. Available online at http://content.nejm.org/cgi/content/abstract/329/24/1753?ck=nck.

Farrow A, Atwal A, Troisi G, Reynolds R. Investigating health effects Investigating health effects of indoor chemicals from common household chemicals products in older products in older people. Brunel University. School of Health Sciences & Social Care & Experimental Techniques Centre Brunel. Available online at http://www.silsoe.cranfield.ac.uk/ieh/ukieg/restricted/191004pres/Farrow.pdf.

Godleski JJ, Verrier RL, Koutrakis P et al. Mechanisms of Morbidity and Mortality From Exposures to Ambient Air Particles. Health Effects Institute Research Report 91. Cambridge, MA. 2000.

Gokhale S, Tibor Kohajda T and Schlink U. Source apportionment of human personal exposure to volatile organic compounds in homes, offices and outdoors by chemical mass balance and genetic algorithm receptor models. Science of The Total Environment, In Press, Corrected Proof. Available online September 25, 2008 at www.sciencedirect.com.

Grandjean P and Perez M. Potentials for exposure to industrial chemicals suspected of causing developmental neurotoxicity. Department of Environmental Health, Harvard School of Public Health. Boston, Massachusetts. Available online at http://www.hsph.harvard.edu/neurotoxicant/appendix.doc.

Jaakkola JJK, Hwang BF, Jaakkola N. Home dampness and molds, parental atopy, and asthma in childhood: a six-year population-based cohort study. Environ Health Perpsect. 113(3): 357 – 361. March 2005.

Jenkins PL, Phillips TJ, Mulberg EJ and Hui SP. Activity patterns of Californians: Use of and proximity to indoor pollutant sources. Atmos. Environ. 26A: 2141-2148. 1992. As reported on the Lawrence Berkeley National Laboratory website http://eetd.lbl.gov/ied/viaq/v_voc_1.html and in Klepeis 2001.

Long CM, Suh HH, Koutrakis P. Characterization of indoor particle sources using continuous mass and size monitors. J Air & Waste Manage Assoc. 2000. 50, 1236 – 1250.

Lu PJ, Youngpairoj S, Bridges C, Herrera G. US children and adults with high-risk conditions. PowerPoint™presentation. Centers for Disease Control and Prevention. Available online at www.hhs.gov/nvpo/meetings/PowerPoints/HerreraHRconditionsInfluenzaPrior041705.ppt.

MacTavish K, Eley M, Salamon S. Policy and Practitioner Perspectives: Housing Vulnerability Among Rural Trailer-Park Households. Georgetown Journal on Poverty Law & Policy. Vol. 8, No 1. Spring 2006.

McDonald B and Ouyang M. Air Cleaning – Particles. Chapter 9 IN: Indoor Air Quality Handbook. Eds: Spengler JD; Samet JM and McCarthy JF. McGraw Hill. New York. 2000.

McGraw-Hill Construction. Green Home Building Market Has “Tipped” and is Expected to Double by 2012, According to New Report from McGraw-Hill Construction. Press release issued on May 12, 2008. Accessed October 1, 2008. Available online at http://construction.com/AboutUs/2008/0512pr.asp.

McGraw-Hill Construction. The Green Home Consumer: Driving Demand for Green Homes. SmartMarket Report. Mc-Graw-Hill Construction. New York. 2008a.

McGraw-Hill Construction. Green Outlook 2009: Trends Driving Change. McGraw-Hill Construction. New York. 2008b.

Moolgavkar SH, Dockery DW, Pope CA. Air pollution and mortality. N Engl J Med. 330:1237-1238, April 28, 1994.

Özkaynak H, Whyatt RM, Needham LL et al. Exposure assessment implications for the design and implementation of the National Children’s Study. Environ Health Perspect. 113 (8): 1108 – 1115. August 2005.

Park JS and Ikeda K. Variations of formaldehyde and VOC levels during 3 years in new and older homes. Indoor Air. (16) 2: 129 – 135. February 7, 2006. Available online at www3.interscience.wiley.com/journal/118604241/abstract?CRETRY=1&SRETRY=0

Penn State Department of Architectural Engineering. Airborne Pathogen Control Technologies. State College, Pennsylvania. 2006. Available online at www.engr.psu.edu/ae/iec/abe/control.asp.

Persily AK, Crum EC, Nabinger SJ and Lubliner M. Ventilation, Humidity Control and Energy Proceedings. Air Infiltration and Ventilation Centre (AIVC) Conference and Building Environment and Thermal Envelope Council (BETEC) Conference, 24th. Proceedings. (International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems Program. Annex V: Air Infiltration and Ventilation Centre.) October 14, 2003. Washington, DC. Pp 295 – 300. 2003. Available online at www.fire.nist.gov/bfrlpubs/build03/art076.html.

Rudel RA, Camann DE, Spengler JE, et al. Phthalates, aklypehnols, pesticides, polybrominated diphenyl ethers, and other endocrine disrupting compounds in indoor air and dust. Environmental Science and Technology (online). September 13, 2003. Available at www.mindfully.org.

Rumchev K, Spickett J, Bulsara M et al. Association of domestic exposure to volatile organic compounds with asthma in young children. Thorax. 59: 746 – 751. 2004.

Sarwar G, Corsi R, Allen D, Weschler C. 2002. Production and levels of selected indoor radicals: a modeling assessment. IN: Proceedings of Indoor Air, The Ninth International Conference on Indoor Air Quality and Climate, June 30 – July 5, 2002, Monterey, Calif.

Sitting. M. Handbook of Toxic and Hazardous Chemicals and Carcinogens. 3rd ed. Vol. 2. Park Ridge, New Jersey. Noyes Publications. 1991. As reported in Underhill 2000.

Solet et al. Childhood asthma hospitalizations – King County, Washington. MMWR 49(41): 929 – 933. October 13, 2000.

Underhill D. Removal of Gases and Vapors. Chapter 10 IN: Indoor Air Quality Handbook. Eds: Spengler JD; Samet JM and McCarthy JF. McGraw Hill. New York. 2000.

US Department of Energy (US DOE). 2005 Housing Characteristics Tables. 2005 Residential Energy Consumption Survey Tables. Energy Information Administration. Washington, DC. Accessed October 1, 2008. Available online at www.eia.doe.gov/emeu/recs/recs2005/hc2005_tables/detailed_tables2005.html.

US Environmental Protection Agency. Residential Air Cleaning Devices: A Summary of Information. Available online at www.epa.gov/iaq/residair.html. Accessed January 31, 2006.

US Environmental Protection Agency. Provisional Assessment of Recent Studies on Health Effects of Particulate Matter. EPA/600/R-06/063. National Center for Environmental Assessment, Office of Research and Development. Research Triangle Park, NC. July 2006.

Weschler C and Shields H. 1999 Indoor ozone/terpene reactions as a source of indoor particles. Atmos. Environ. Vol. 33, pp 2301 – 2312.

Wiley JA, Robinson JP, Cheng YT et al. Study of children's activity patterns. Survey Research Center, University of California, Berkeley (ARB Contract No: A-33149). California Air Resources Board Research Notes. No. 94-6. April 1994. Sacramento, California. Available online at http://www.arb.ca.gov/research/resnotes/notes/94-6.htm.

Wolkoff P, Clausen PA, Wilkins CK et al. (2000). Formation of strong airway irritants in terpene/ozone mixtures. Indoor Air 10: 82 – 91.

Zota AR, Rudel RA, Morello-Frosch RA et al. Elevated house dust and serum concentrations of PBDEs in California: Unintended Consequences of Furniture Flammability Standards? Environ Sci Technol. Published on the web October 1, 2008. Available online at http://pubs.acs.org/cgi-bin/sample.cgi/esthag/asap/html/es801792z.html.